

REACTION $pp \rightarrow \{pp\}_s \pi^0$ IN THE GeV REGION AND $\pi^0 p$ RESCATTERING

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Abstract

COSY data on the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$, where $\{pp\}_s$ is the proton pair in the 1S_0 state at small excitation energy $E_{pp} = 0 - 3$ MeV, recently obtained for beam energies 0.5 - 2.0 GeV are analyzed within the one-pion exchange model. The model is based on the subprocess $\pi^0 p \rightarrow \pi^0 p$ and final state pp-interaction. A broad maximum observed in the energy dependence of the cross section at 0.5 - 1.4 GeV in the forward direction is explained by this model as a dominant contribution of the isospin $\frac{3}{2}$ in the $\pi^0 p$ -rescattering. The second maximum observed at 2 GeV is underpredicted within the model by one order of magnitude.

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1 Introduction

Study of the reaction $pp \rightarrow \{pp\}_s \pi^0$, where $\{pp\}_s$ is the proton pair (diproton) in the 1S_0 state at small excitation energy $E_{pp} = 0 - 3$ MeV, is motivated by several reasons. First, this is the simplest inelastic process in the pp-collision, which can reveal underlying dynamics of NN interaction. Second, restriction to only one pp-partial wave (s-wave) in the final state considerably simplifies a comparison with theory making it basically similar to that for the other simplest reaction of this type, $pp \rightarrow d\pi^+$. However, while for the reaction $pp \rightarrow d\pi^+$ there are a lot of data including spin observables [1], which are used to test theoretical models in the GeV region [2, 3], data on the reaction $pp \rightarrow \{pp\}_s \pi^0$ above 0.4 GeV were absent until recent measurements at COSY [4, 5]. Third, the quasi-binary reaction $pp \rightarrow \{pp\}_s \pi^0$ is very similar kinematically to the reaction $pp \rightarrow d\pi^+$, but its dynamics can be essentially different. In fact, quantum numbers of the diproton state ($J^\pi = 0^+$, $I = 1$, $S = 0$, $L = 0$) differ from these for the deuteron ($J^\pi = 0^+$, $I = 0$, $S = 1$, $L = 0, 2$). Therefore, transition matrix elements for these two reactions are also different. Using the generalized Pauli principle and angular momentum and P-parity conservation, one can easily find that only negative parity states are allowed in the reaction $pp \rightarrow \{pp\}_s \pi^0$. Thus, for the intermediate ΔN state odd partial waves (p-, f-, ...) are allowed, whereas even waves (s-, d-, ...) are forbidden. Therefore, at the nominal $\Delta(1232)$ -threshold of the reaction $NN \rightarrow \Delta N$, $T_p = 0.63$ GeV, the lowest allowed partial wave is the p-wave, which, however, has to be suppressed by the centrifugal barrier.

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In contrast, in the $pp \rightarrow d\pi^+$ reaction both negative and positive parity $\Delta - N$ states are allowed. As a consequence, the relative contribution of the Δ -mechanism to the reaction $pp \rightarrow \{pp\}_s\pi^0$ is expected to be suppressed as compared to the reaction $pp \rightarrow d\pi^+$. This argument was applied in Ref. [6] to explain a very small ratio (less of few percents) of the spin-singlet to spin-triplet pn-pairs observed in the LAMPF data [7] in the final state interaction region of the reaction $pp \rightarrow pn\pi^+$ at proton beam energy 0.8 GeV. Obviously, this argument is valid for any intermediate N^*N - states with other nucleon isobars N^* of positive parity. Furthermore, since Δ -type mechanisms are of long-range type, reduction of their contribution would mean that other mechanisms, like N^* -exchanges [8] which are more sensitive to short-range NN-dynamics, could be more important in the reaction $pp \rightarrow \{pp\}_s\pi^0$ as compared to the $pp \rightarrow d\pi^+$ reaction [9].

The cross section of the reaction $pp \rightarrow \{pp\}_s\pi^0$ was measured recently at energy 0.8 GeV in Ref.[4] and at beam energies 0.5 - 2.0 GeV in Ref. [5]. (For measurements at energies below 0.425 GeV see Refs.[10, 11, 12].) At the zero angle, the data [5] show a broad maximum in the energy dependence of the cross section at 0.5 -1.4 GeV. This maximum is similar in shape and position to the well known Δ - maximum in the reaction $pp \rightarrow d\pi^+$. However, a comparison with the calculation [13] performed within a microscopical model, which includes $\Delta(1232)$ -isobar excitation and s-wave πN -rescattering, shows very strong disagreement between the model and the data obtained at energies 0.5 - 0.9 GeV [5] both in the absolute value and shape of energy dependence of the cross section. So, the forward cross section measured in Ref. [5] is lower than the calculated one [13] by factor of three at 0.6 GeV, where the Δ -isobar maximum would be expected, whereas at 0.5 and 0.8 GeV the disagreement is more than one order of magnitude [5].

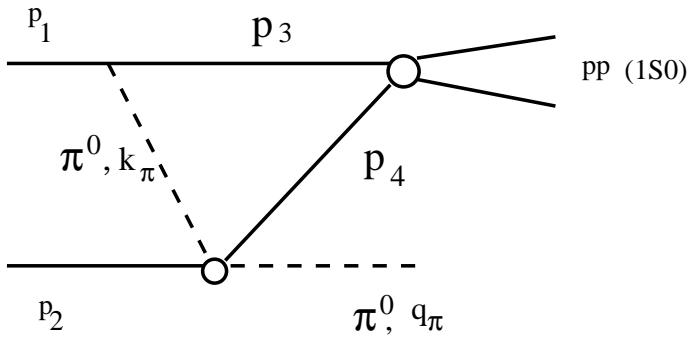


Figure 1: The OPE mechanism of the reaction $pp \rightarrow \{pp\}_s\pi^0$.

In view of qualitative arguments given above, this disagreement would mean that either the model of Ref. [13] is incorrect, or the observed maximum of the cross section of the reaction $pp \rightarrow \{pp\}_s\pi^0$ at 0.5 - 1.4 GeV is of non- Δ -isobar origin ². Here we analyse these data employing a simpler model, which includes the subprocess $\pi^0 p \rightarrow \pi^0 p$ and the final state $pp(^1S_0)$ -interaction (Fig.1). We show that the observed shape of the

²It was supposed in Ref.[5] that the observed maximum is caused by the Δ -isobar contribution, but no theoretical calculation were performed to confirm it.

peak and, to a large extent, its magnitude are in agreement with the dominance of the $\Delta(1232)$ -isobar contribution.

1.1 The model

We consider the reaction $pp \rightarrow \{pp\}_s \pi^0$ within the mechanism which corresponds to the triangle diagram in Fig. 1. A very similar mechanism was successfully applied for analysis of the $pp \rightarrow d\pi^+$ reaction in the region of the $\Delta(1232)$ -isobar [14, 15] and at higher energies too [14].

The amplitude of the reaction $pp \rightarrow \{pp\}_s \pi^0$ consists of two terms, $A = A^{dir} - A^{exch}$, where A^{dir} is the direct term and A^{exch} is the exchange one. These terms are related to one another by permutation of two initial protons. The one-loop integral for the direct term A^{dir} is evaluated very similarly to the OPE-II model of the reaction $pd \rightarrow \{pp\}_s n$ considered in Ref.[16]. Thus, A^{dir} takes the following form:

$$A^{dir}(p_1, \sigma_1, p_2, \sigma_2) = \frac{f_{\pi NN}}{m_\pi} N_{pp} 2m_p F_{\pi NN}(k_\pi^2) \times \quad (1)$$

$$\times \Sigma_{\sigma_3 \sigma_4 \mu} (\frac{1}{2} \sigma_3 \frac{1}{2} \sigma_4 | 00) (1 \mu \frac{1}{2} \sigma_3 | \frac{1}{2} \sigma_1) J^\mu(\tilde{p}, \gamma) A_{\sigma_2}^{\sigma_4}(\pi^0 p \rightarrow \pi^0 p),$$

here $f_{\pi NN}$ is the πNN coupling constant with $f_{\pi NN}^2/4\pi = 0.0796$, $F_{\pi NN}(k_\pi^2) = (\Lambda^2 - m_\pi^2)/(\Lambda^2 - k_\pi^2)$ is the πNN form factor, k_π is the four-momentum of the virtual π -meson, m_p (m_π) is the nucleon (pion) mass, σ_i ($i = 1, \dots, 4$) is the z-projection of the spin of i th proton; $A(\pi^0 p \rightarrow \pi^0 p)$ is the amplitude of the $\pi^0 p$ elastic scattering which is taken on-mass-shell; the vector J_μ is defined by the transition form factors as

$$J^\mu(\tilde{p}, \gamma) = \sqrt{\frac{E_1 + m_p}{2m_p}} \frac{m_p}{E_1} \{ R^\mu F_0(\tilde{p}, \gamma) - i \hat{\tilde{p}}^\mu \Phi_{10}(\tilde{p}, \gamma) \}, \quad (2)$$

where

$$F_0(\tilde{p}, \gamma) = \int_0^\infty dr r j_0(\tilde{p}r) \psi_k^{(-)*}(r) \exp(-\gamma r), \quad (3)$$

$$\Phi_{10}(\tilde{p}, \gamma) = i \int_0^\infty dr j_1(\tilde{p}r) \psi_k^{(-)*}(r) (1 + \gamma r) \exp(-\gamma r), \quad (4)$$

here $j_l(x)$ ($l = 0, 1$) is the spherical Bessel function, $\psi_{\mathbf{k}}^{(-)}(\mathbf{r})$ is the pp-scattering wave function that is the solution of the Schrödinger equation at the cms momentum $|\mathbf{k}|$ with the interaction potential $V(^1S_0)$ for the following boundary condition at $r \rightarrow \infty$:

$$\psi_{\mathbf{k}}^{(-)}(\mathbf{r}) \rightarrow \frac{\sin(kr + \delta)}{kr}. \quad (5)$$

Here δ is the 1S_0 phase shift (for simplicity we omit here the Coulomb interaction, which is taken into account in real numerical calculations). In Eq.(1) the combinatorial factor

$N_{pp} = 2$ takes into account identity of two protons. Kinematical variables in Eqs. (2) - (4) are defined as

$$\gamma^2 = \frac{T_1^2}{(E_1/m_p)^2} + \frac{m_\pi^2}{E_1/m_p}, \quad \mathbf{R} = -\mathbf{p}_1 \frac{m_p T_1}{(E_1 + m_p) E_1}, \quad \tilde{\mathbf{p}} = \frac{\mathbf{p}_1}{E_1/m_p}, \quad (6)$$

where E_1 , \mathbf{p}_1 and $T_1 = E_1 - m_p$ are the total energy, 3-momentum and kinetic energy of the initial proton p_1 , respectively, in the rest frame of the final diproton. The exchange amplitude A^{exch} can be obtained from Eqs.(1)-(6) by interchanging $1 \leftrightarrow 2$.

The OPE cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ in the cm system is

$$\frac{d\sigma}{d\Omega} = \frac{1}{(4\pi)^5} \frac{p_f}{s_{pp} p_i} \int_0^{k^{max}} dk^2 \frac{k}{\sqrt{m_p^2 + k^2}} \frac{1}{2} \int d\Omega_{\mathbf{k}} |\overline{A_{fi}}|^2, \quad (7)$$

where k^{max} is the maximal relative momentum in the final pp-system, related to the maximal relative energy E^{max} as $k^{max} = \sqrt{E^{max} m_p}$, p_i (p_f) is the cms momentum in the initial (final) state of the $pp \rightarrow \{pp\}_s \pi^0$ reaction, s_{pp} is the squared invariant mass of the initial pp-system. The factor $\frac{1}{2}$ in front of the integral over directions of \mathbf{k} takes into account identity of two final protons. Keeping only the direct term of Eq.(1), one can finally find from Eq. (7)

$$\begin{aligned} \frac{d\sigma}{d\Omega_\theta} (pp \rightarrow \{pp\}_s \pi^0) &= \frac{1}{24\pi^2} \frac{p_f}{p_i} \frac{s_{\pi p}}{s_{pp}} \left[\frac{f_{\pi NN}}{m_\pi} N_{pp} m_p F_{\pi NN}(k_\pi^2) \right]^2 \times \\ &\times \int_0^{k^{max}} dk \frac{2k^2}{\sqrt{m_p^2 + k^2}} \left\{ 2|J^{\mu=0}(\tilde{p}, \delta)|^2 + |J^{\mu=1}(\tilde{p}, \delta)|^2 \right\} \frac{d\sigma}{d\Omega_\phi} (\pi^0 p \rightarrow \pi^0 p). \end{aligned} \quad (8)$$

The differential cross section of the reaction $\pi^0 p \rightarrow \pi^0 p$ is taken in Eq. (8) at the squared invariant mass of the πp system, $s_{\pi p}$, defined as

$$s_{\pi p} = (m_\pi + m_p)^2 + 2T_\pi m_p. \quad (9)$$

Here T_π is the kinetic energy of the final meson π^0 in the rest frame of the final diproton. If θ is the angle between the cms momenta of the diproton and the proton p_1 , which emits the virtual pion in the direct OPE diagram in Fig.1, and ϕ is the cms scattering angle of the π^0 -meson in the process $\pi^0(k_\pi) + p_2 \rightarrow p_4 + \pi^0(q_\pi)$, then one can find the following relation:

$$p_{20} q_0 + |\mathbf{p}_2| |\mathbf{q}_\pi| \cos \phi = \sqrt{m_p^2 + p_i^2} \sqrt{m_\pi^2 + p_f^2} - p_i p_f \cos \theta, \quad (10)$$

where the four-momenta of the initial proton $p_2 = (p_{20}, \mathbf{p}_2)$ and the final π^0 -meson $q_\pi = (q_0, \mathbf{q}_\pi)$ in the cms of the πp system can be written as

$$\begin{aligned} p_{20} &= \frac{1}{2\sqrt{s_{\pi p}}} (s_{\pi p} + m_p^2 - k_\pi^2), \quad q_0 = \frac{1}{2\sqrt{s_{\pi p}}} (s_{\pi p} + m_\pi^2 - m_p^2), \\ |\mathbf{q}_\pi| &= \sqrt{q_0^2 - m_\pi^2}, \quad |\mathbf{p}_2| = \sqrt{p_{20}^2 - m_p^2}. \end{aligned} \quad (11)$$

The squared four-momentum of the intermediate π -meson is

$$k_\pi^2 = 2m_p^2 + p_i p_f \cos \theta - \sqrt{m_p^2 + p_i^2} \sqrt{M_{pp}^2 + p_f^2}, \quad (12)$$

where M_{pp} is the mass of the final diproton. One can find from Eqs. (10), (11) and (12) that backward $\pi^0 p$ scattering ($\phi = 180^\circ$) dominates diproton formation in the forward direction ($\theta = 0^\circ$).

Analysis of the reaction $pp \rightarrow d\pi^+$ in the Δ region, performed in Refs. [15] shows that the contribution of the pole diagram with the neutron exchange is small but non-negligible and being added to the OPE diagram with πN rescattering improves the agreement with the data. For the reaction $pp \rightarrow \{pp\}_s \pi^0$ a similar pole diagram seems to be less important and is not taken into account here. The point is that at $T_p = 0.5 - 2.0$ GeV and $\theta = 0^\circ$ the $pp \rightarrow \{pp\}_s$ vertex in the pole diagram of the reaction $pp \rightarrow \{pp\}_s \pi^0$ involves the high momentum component of the wave function $\psi_{\mathbf{k}}^{(-)}(\mathbf{q})$ at the relative momentum between protons $q = 0.4 - 0.6$ GeV/c, but in contrast to the $pn \rightarrow d$ vertex, does not contain the D-wave which is important for the pole diagram at large q . Furthermore, the S-wave component has a node at $q \approx 0.4$ GeV/c (see, for example, Ref.[16]).

2 Numerical results and discussion

In numerical calculation we used the data on the elementary πN reactions from SAID [1]. The scattering wave function $\psi_{\mathbf{k}}^{(-)}(\mathbf{r})$ of the pp system at low energy < 3 MeV is largely independent of the NN model and is calculated here using the Reid soft core potential plus Coulomb interaction [17]. The calculated forward cross section multiplied by the factor 0.45 is shown in Fig. 2. When comparing the dotted and full lines in Fig. 2, one can see that the contribution of the exchange term $|A^{exch}|^2$ is much less important than the direct term $|A^{dir}|^2$ at $\theta = 0^\circ$. Thus, we neglect below the term A^{exch} . As seen from Fig. 1, the OPE model is in good agreement with the observed shape of the cross section at 0.5 - 1.4 GeV. Note that the form factors $F_0(\tilde{p}, \gamma)$ and $\Phi_{10}(\tilde{p}, \gamma)$ in Eq. (2) are smooth functions of the beam energy T_p . Therefore, the calculated shape of the $pp \rightarrow \{pp\}_s \pi^0$ cross section follows mainly the T_p -dependence of the $\pi^0 p \rightarrow \pi^0 p$ cross section at the cms angle $\phi = 180^\circ$. The disagreement in absolute value by factor 0.45 corresponds to a typical factor of absorptive distortions in the initial pp state [18]. The distortions are not taken into account in the present work in view of their dependence on unknown details of the production mechanism, in particular, on off-shell behaviour of the $\pi^0 p$ -scattering amplitude. Furthermore, one should note that when calculating the diagram in Fig.1, we factor the amplitude of the elastic $\pi^0 p$ scattering outside the integral sign. Within this approximation, the contribution of intermediate $\Delta - N$ states of positive parity is not excluded from this reaction as it should be in an exact OPE amplitude according to the discussion in the Introduction. For this reason, this simple model cannot provide a precise absolute value of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$. The disagreement in the absolute value of the cross section can be also related in part to the neglected off-shell effects in the $\pi^0 p \rightarrow \pi^0 p$ amplitude and contribution of the mesons η , η' and ω .

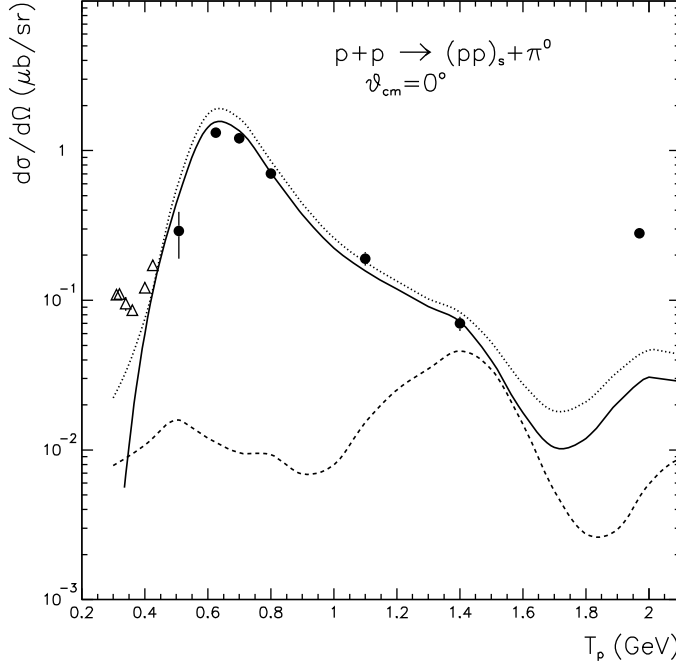


Figure 2: The cms cross sections of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at $\theta = 0^\circ$ versus beam energy. Data are taken from Ref. [12] (\triangle) and [5] (\bullet). The dotted curve presents the calculated cross section for the incoherent sum of the direct and exchange terms of the OPE model amplitude. Other curves are obtained with the direct term A^{dir} only for the isospin term $a_{\frac{3}{2}}$ excluded from (dashed line) and included (full line) in the $\pi^0 p \rightarrow \pi^0 p$ amplitude, as explained in the text. All curves are scaled by the factor 0.45.

In order to exhibit sensitivity of the calculated cross section to the Δ -isobar contribution, one can completely exclude the contribution of the isospin $\frac{3}{2}$ from the $\pi^0 p$ scattering. The isospin decomposition of the $A(\pi^0 p \rightarrow \pi^0 p)$ amplitude is the following:

$$A(\pi^0 p \rightarrow \pi^0 p) = \frac{1}{3} \left(a_{\frac{1}{2}} + 2a_{\frac{3}{2}} \right), \quad (13)$$

here $a_{\frac{1}{2}}$ ($a_{\frac{3}{2}}$) is the amplitude with the total isospin $\frac{1}{2}$ ($\frac{3}{2}$). The cross section of the $\pi^0 p$ elastic scattering can be written as

$$d\sigma(\pi^0 p \rightarrow \pi^0 p) = \frac{1}{2} \left\{ d\sigma(\pi^+ p) + d\sigma(\pi^- p) - d\sigma(\pi^0 n \rightarrow \pi^- p) \right\}, \quad (14)$$

where $d\sigma(\pi^+ p)$, $d\sigma(\pi^- p)$ and $d\sigma(\pi^0 n \rightarrow \pi^- p)$ are the differential cross section of the $\pi^+ p$ and $\pi^- p$ elastic scattering and charge exchange reaction $\pi^0 n \rightarrow \pi^- p$, respectively. After the amplitude $a_{\frac{3}{2}}$ is excluded from Eq. (13), the cross section of the $\pi^0 p$ scattering takes the form

$$d\tilde{\sigma}(\pi^0 p \rightarrow \pi^0 p) = \frac{1}{18} \left\{ 3d\sigma(\pi^- p) - d\sigma(\pi^+ p) + 3d\sigma(\pi^0 n \rightarrow \pi^- p) \right\}. \quad (15)$$

In order to exclude the term $a_{\frac{3}{2}}$ from the $\pi^0 p$ elastic scattering in calculation of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ one should substitute Eq. (15) instead of Eq. (14) into Eq. (8). When we do so, the absolute value of the calculated cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.4 - 1.1 GeV diminishes by two orders of magnitude and comes in strong contradiction with the data (see dashed line in Fig. 2). Since the amplitude $a_{\frac{3}{2}}$ of the πN elastic scattering is dominated by the $\Delta(1232)$ -isobar at $\sqrt{s_{\pi N}} \sim 1.15 - 1.35$ GeV, this analysis shows that the excitation of the $\Delta(1232)$ -isobar dominates in the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1.0 GeV too. On the other hand, since the s -wave intermediate $\Delta - N$ state is forbidden, but was not excluded from the reaction amplitude within this model, the agreement obtained between the calculated and measured shape of the cross section suggests that the absence of this s -state in an exact OPE amplitude would be not so crucial for the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.4-1.1 GeV, as might follow from the qualitative arguments given in the Introduction. In other words, it would mean that the p -wave and higher odd waves are not suppressed drastically by centrifugal barrier (perhaps, due to long-range character of the $\Delta - N$ interaction) and make a large enough contribution to this reaction.

Let us make some further comments. Firstly, the second maximum of the forward $pp \rightarrow \{pp\}_s \pi^0$ cross section is observed at 1.97 GeV. The forward $pp \rightarrow d\pi^+$ cross section exhibits a similar maximum [1]. This peculiarity of the $pp \rightarrow d\pi^+$ cross section was interpreted in Ref. [14] within the OPE model as a manifestation of heavy nucleon resonances in the elastic πN scattering. One can see from Fig. 2 that the OPE model considerably underestimates the magnitude of the observed second maximum in the $pp \rightarrow \{pp\}_s \pi^0$ cross section. One may suppose that excitation of heavy Δ 's is not sufficient to explain the data at 2 GeV and, therefore, other mechanisms of this reaction like N^* exchange or Reggeon exchange recently discussed in Ref. [16] make a sizeable contribution in this region. To choose between the heavy Δ -isobars excitation and the N^* (or Reggeon) exchange mechanism one should measure the ratio of the cross sections $pp \rightarrow \{pp\}_s \pi^0$ and $pn \rightarrow \{pp\}_s \pi^-$ [16].

Secondly, as can be shown, the present model predicts a smooth increase (5-15%) of the differential cross section in forward direction at $\theta = 0^\circ - 15^\circ$, that is in qualitative agreement with the data at 2 GeV, but in disagreement at lower energies. A more detailed model, with distortions and explicit Δ -isobars included, has to be developed to describe the angular dependence of the cross section. This kind of model considered in Ref. [13] below 0.9 GeV was to some extent successful in this respect, while failed to describe the energy dependence.

3 Conclusion

Arguments, based on parity and angular momentum conservation, show that the S -wave ΔN -intermediate state is forbidden in the reaction $pp \rightarrow \{pp\}_s \pi^0$, when the final pp -pair is produced in the 1S_0 -state. The microscopical model [13], which takes into account this specific feature of the reaction $pp \rightarrow \{pp\}_s \pi^0$, since includes explicitly the Δ -isobar contri-

bution via coupled NN – and $N\Delta$ –channels, is in strong disagreement with the observed energy dependence of the recently measured cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1 GeV. On the other hand, a rather simple OPE model developed in the present work, which includes the subprocess $\pi^0 p \rightarrow \pi^0 p$ and the final state $pp(^1S_0)$ -interaction, reproduces the observed shape of energy dependence of the cross section of the reaction $pp \rightarrow \{pp\}_s \pi^0$ at 0.5 - 1.4 GeV and to some extent agrees with its absolute value. Thus, the OPE model clearly exhibits dominance of the $\Delta(1232)$ -isobar in this region, although the angular dependence of the $pp \rightarrow \{pp\}_s \pi^0$ cross section is not described within this simple model. One should note, that a quite similar OPE model was recently successfully applied to the $pd \rightarrow \{pp\}_s n$ reaction in Ref.[16] just in the Δ -isobar region. Therefore, a failure of the model of Ref. [13], most likely, is related not to the Δ contribution itself, but rather caused by interference effects with other terms, for example, with phenomenological heavy meson exchange. More insight into the dynamics of the single pion production in pN collision can be gained by further measurement of the reaction $pn \rightarrow \{pp\}_s \pi^-$ at the same kinematical conditions. It would be also interesting to get data on the reaction $pp \rightarrow \{pp\}_s \pi^0$ at higher excitation energy of the final pp-pair, $E_{pp} = 3 - 10$ MeV, where small components of the pp-wave function start to contribute and allow the S-wave intermediate ΔN – state.

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